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Lubrication film flow control by oriented dimples for liquid lubricated mechanical seals

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ABSTRACT

Apart from the function such as micro-hydrodynamic bearings, lubrication reservoir and debris traps, surface textures can be used to control the lubricant's flow. In this paper, the leak control feasibility is numerically validated by processing some different oriented dimples on the mechanical seals, including the elliptical, diamond, triangular and rectangular shapes. The streamline-Upwind/Petrov–Galerkin (SUPG) finite element method is used to solve the Reynolds equation by considering mass conservation. Parametric study is performed to analyze the effect of the geometric parameter on the sealing performance such as the flow rate and the load-carrying capability. The reverse pumping capability is compared among these oriented dimples.

1. Introduction

Mechanical seal is widely applied in the industrial fields to prevent the high pressure fluid escaping from the rotary machinery, such as pumps, compressors, mixers and so on. It mainly consists of a couple of rings (the stator and the rotor) respectively sitting on the house and the shaft (in Fig. 1). Under the action of the spring force and the hydrostatic pressure, the ring couples align perfectly and slide against each other along the circumferential direction. The sealed fluid will leak through the gap between the couples, which is the main leak path of the mechanical seal. This leakage should be limited and controlled to avoid pollution. In addition, controlling leakage is helpful for improving the lubrication and minimizing the temperature rise of the seal faces.

Several measurements have been taken to avoid face wear and large leakage between the faces. One way is to process the hydrodynamic grooves on the face of rings. These grooves can be chosen as spiral grooves, circular grooves or herringbone grooves et al. They are used not only to control the leakage, but also to provide the hydrodynamic effect and to improve the lubrication. Their effects have been thoroughly investigated in the past decades. Zero leakage design is the ultimate goal of the seal engineers. Etsion [1] presented a kind of zero-leakage multilobes seal configuration by which the balance is achieved between the pressure-induced flows and the shear-induced ones. Later, Lipschitz [2] proposed another zero-leakage hydrodynamic mechanical seal, whose mechanism is the pumping effect of the hydrodynamic bearings distributed evenly at angular intervals. Lai [3] tested in field the leakage control feasibility of the herringbone pattern and the 'y' type grooves. Lebeck [4] experimentally and theoretically studied the zero leakage backward pumping mechanical seals based on the foamy lubrication model. Moreover, Upstream pumping mechanical seals [5] and Laserface mechanical seals [6] are two kinds of modern sealing technology in which the groove patterns pump the fluid back and the flow of the sealed fluid is controlled.

Apart from the above hydrodynamic grooves, the leak or the flow of the sealed fluid can be controlled by the surface textures with the oriented dimples or asperities. As the well-known surface engineering technology, this technology has been widely employed in sliding bearings [7,8], mechanical seals [9], lip seals [10], piston rings [11,12] and metal forming [13]. Plenty of research works have been done on the lubrication mechanism [14] and the optimal design of the dimple patterns. Most of the dimples are circle-like cavities; others include the triangular, elliptical, rectangular or hexagonal dimples. The function of these surface patterns includes the micro-hydrodynamic bearings, the lubricant reservoirs and the debris traps. Brunetière studied the difference in sealing performance between the smooth-textured surfaces and the rough-textured ones and found that the formers are unable to generate enough load to separate the seal surfaces [15]. Qiu et al. [16,17] found that the texture shape has a great impact on the load-carrying capacity (LCC) and the dynamic characteristics of gas-lubricated parallel slider bearings. Razzaque et al. [18] and Shen et al. [19] investigated the effect of the internal structure of the microspores on the hydrodynamic lubrication and the sealing performance. Yu et al. [20,21] and Yuan et al. [22] pointed out that the orientation of the surface textures has an impact on the lubrication. They found that the elliptical dimples with the major

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Nomenclature

a	length of major axis of dimples
b	length of minor axis of dimples
c	seal gap
F_O	load-carrying capacity (LCC) or open force
h,H	film thickness of lubricant ($H=h/c$)
m	dimple number along the circumferential direction
n	dimple number along the radial direction
p,P	fluid film pressure ($P=(p-p_c)/(p_a-p_c)$)
Q	dimensionless flow rate
r,R	radius on seal face ($R=r/r_i$)
S	dimple area ratio
U	sliding velocity
w	weighted function
x,X	Cartesian coordinate ($X=x/r_i$)
y,Y	Cartesian coordinate ($Y=y/r_i$)

Greeks

α	orientation angle of dimples
Λ	dimensionless seal number ($\Lambda=3\mu r_i\omega/(\pi c^2(p_a-p_c))$)
λ	ratio of major axis length to minor one ($\lambda=b/a$)
μ	lubricant viscosity
ρ	lubricant density
θ	fraction of liquid in the lubrication film
ω	angular speed of rotor

Abbreviation

a	atmosphere
c	cavitation
i	inner
L	liquid
o	outer
p	dimple
SUPG	Streamline-Upwind/Petrov–Galerkin

axis perpendicular to the sliding direction show larger LCC than the one parallel to the sliding direction. Syed [23] gave similar numerical results by taking Reynolds cavitation boundary conditions into consideration in his mathematical model. Xie [24] numerically investigated the hydrostatic effect of the rectangular texture on the liquid-lubricated mechanical seals and pointed out that the influence of the orientation factor is remarkable on the sealing performance. The numerical and experimental investigations on the effectiveness of controlling the flow by the oriented triangles were conducted by Li [25] for the lip seals. He attributed this ability to the directional pumping mechanism of the surface textures. Some other researchers also found that the oriented surface textures provides higher LCC [26] or stronger control capability of the lubricants flow [27]. To sum up, the reverse pumping capability of the oriented surface textures can be recognized as its' fourth profit. However, this mechanism hasn't been completely understood by the researchers until now.

The purpose of this paper is to verify the feasibility of controlling the leak by the design of the oriented dimples evenly distributed on the mechanical seal face. Four kinds of oriented dimples, including diamond (*D*), ellipse (*E*), rectangle (*R*) and triangle (*T*), are to be investigated to analyze the effect on the reverse pumping capacity and LCC. The Reynolds equation with mass conservation is solved by the SUPG finite element method which has been verified faster than the finite difference method.

2. Analytical models

2.1. Geometrical models

A mechanical seal configuration consists of a rotor and a stator is shown in Fig. 1, where the inside radius and the outside radius of the seal face are set as $r_i=24$ mm, $r_o=34$ mm. The rotor rotates along the clockwise direction at an angular speed ω. The main leak path with thickness c locates between the rings, through which the sealed medium flows away from the seal chamber. The seal face configuration studied in this paper is illustrated in Fig. 2. Four kinds of oriented dimples: diamond, ellipse, rectangle and triangle, are processed on the stator face. The dimples evenly distribute on the stator face along the radial and circumferential direction. There are 150 columns of dimples with 10 dimples in every column on the face. The bottom of the dimples is flat, and the dimple depth is denoted by h_p.

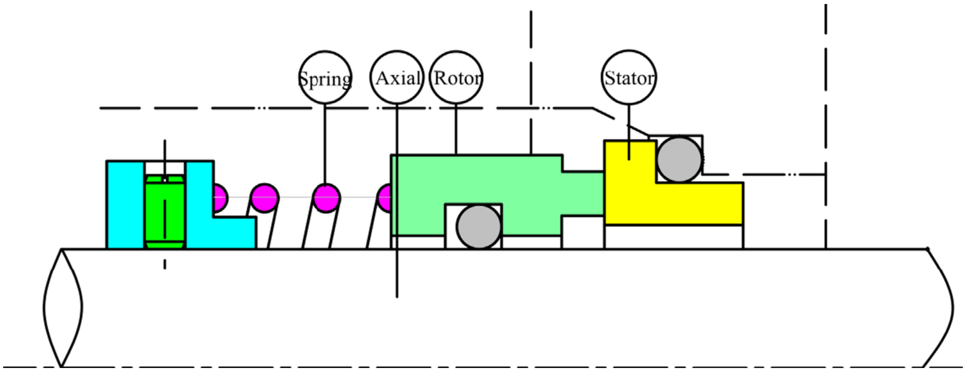

Fig. 1. Schematic of mechanical seals.